12.1 AIR-WAVE-SEA INTERACTION AND ITS APPLICATION TO OCEAN CIRCULATION-WAVE COUPLING

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1. INTRODUCTION

Momentum and energy transfers across the air-sea interface are important not only in theoretical studies, but also in many applications including atmospheric and oceanic forecast and climate modeling on all scales. Breaking waves have been shown to be an important supplier of turbulent energy, in addition to traditional shear production in the air-sea system. Breaking waves also play an important role in the development of thermo-dynamical and turbulent structures in the ocean. It is known that waves contain a considerable amount of momentum and energy, and they redistribute these quantities over great distances. Wind waves supply energy for currents and turbulence due to breaking. The air-sea system on all scale is strongly affected by ocean waves.

A part of the energy and momentum is transferred directly from the atmosphere to ocean currents while another part is transferred to surface waves. Wind waves are result from interaction at the air-sea interface and affect the turbulence of the atmospheric and oceanic surface layers that results in the transport of energy, momentum, heat and moisture. The character of this transport is regulated by the turbulence of the surface layers. These influences are complex and still poorly understood, although there have been numerous experimental investigations and quantitative studies. One of the major difficulties in air-sea interaction problems is the correct description of the surface-wave layer (Fig. 1).

Based on a new concept of turbulence at the air-sea interface (Ly, 1986; 1995; Ly and Garwood, 2000; Ly and Benilov, 2002) and a wave breaking condition model (Longuet Higgins, 1969; Komen at al., 1994), an air-wave-sea coupled model has been developed with a new surface wave parameterization. The model outputs are compared with available data on wave-dependent turbulence dissipation, roughness length, drag coefficient, and momentum fluxes. The air-wave-sea coupled model results are applied to an ocean circulation-wave coupling study in the Florida West Coast (FWC).

In the ocean circulation-wave coupling study, the NAval postgraduate school ocean Model (NAM, Ly and Garwood, 2002) is used. The study is focused on the sensitivity of the current field to the surface waves and on a demonstration of the capability of the NAM model to reproduce an observed upwelling feature for the FWC region.

2. AIR-WAVE-SEA COUPLED MODEL

a. The Coupled Model with a Wave Parameterization

In addition to traditional shear production in the air-sea system, a new turbulence concept considers surface waves to be an important supplier of turbulent energy. A

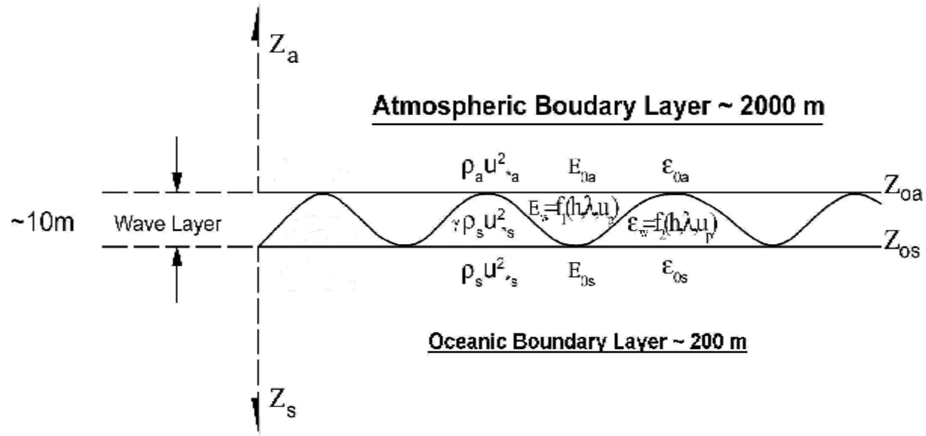

Figure 1. The atmospheric boundary layer is coupled to the oceanic boundary layer and the wave layer is between with wave-dependent roughness lengths from above, z_{0a}, and below, z_{0z}. The surface TKE, E, and ε are expressed as functions of wave parameters.

turbulence closure with a surface-wave parameterization with a wave-dependent roughness length is used in an air-wave-sea coupled model (Ly and Garwood, 2000). Fig. 1 shows the model domain. The wave-dependent roughness length from above (RA) and below (RB) z_{0i} (with $i=a$ for the atmosphere and $i=s$ for ocean) has a form:

$$z_{0a} = a_i\, u_{*a}^{\;2} / g c_w \qquad (1)$$

Here, a_i is empirical constants in RA/RB; u_{*a} is friction velocity; g is gravity and c_w is wave age. For simplicity, RA and RB are taken equal with a_i = 0.3. For developed waves with wave age c_w = 20-30, this roughness length reduces to Charnock's formulation (Charnock, 1955) with Charnock constant of 0.01-0.015.

b. Boundary Conditions

Based on conservation of energy, similarity theory, and a breaking wave condition model, we can have boundary conditions for TKE (E), ε, and surface velocity in terms of momentum flux and wave parameters. The model outputs are compared with all available wave-dependent observed data of ocean turbulent dissipation (ε) distribution, wave-dependent roughness length (z_{0a}), drag coefficient (c_d), and momentum fluxes. Numerical experiments have been shown that waves have an important role in causing ε to differ from the classical wall-layer theory and z_{0a} has an empirical constant of value of 0.30. The model-predicted ε, and wave-dependent z_{0a}, and c_d agree well with data. In next paragraph we present the coupled model results applied to the ocean circulation-wave coupling.

3. APPLICATION TO OCEAN CIRCULATION-WAVE COUPLING

a. The Ocean Circulation Model

The equations for momentum, temperature and salinity contain the vertical turbulent exchange coefficients that are determined by a turbulence closure scheme with a surface wave parameterization (Ly and Garwood, 2002; Ly and Benilov, 2002). This scheme consists of equations for the turbulent kinetic energy (TKE), E, for the turbulent dissipation, ε, and for turbulent exchange coefficient, K_m, and wind-wave-turbulence-current relation equations. The equation for TKE can be written as follows

$$\partial E/\partial t + \vec{U}.\nabla E + W\ \partial E/\partial z = \alpha_1 K_m\ [(\partial U/\partial z)^2 + (\partial V/\partial z)^2 - \alpha_3\ g/\alpha_1\ \rho_0\ \partial\rho/\partial z] + \alpha_4\ \partial/\partial z\ (K_m\ \partial E/\partial z) - \alpha_2\ E^2/K_m + F_e, \quad (2)$$

The equation for ε has the form

$$\partial\varepsilon/\partial t + \vec{U}.\nabla\ \varepsilon + W\ \partial\ \varepsilon/\partial z = \beta_1 K_m\ [(\partial U/\partial z)^2 + (\partial V/\partial z)^2 - \beta_3\ g/\beta_1\ \rho_0\ \partial\rho/\partial z]\ (\varepsilon/E) + \beta_4\ \partial/\partial z\ (K_m\ \partial\ \varepsilon/\partial z) - \beta_2\ \varepsilon^2/E + F_\varepsilon, \quad (3)$$

F_e in equation (2) and F_ε in equation (3) are the horizontal mixing terms, which are similar to F_θ in equations for temperature and salinity. The first two terms on the right-hand side (RHS) in (2) and (3) represent shear production. The next terms are the buoyancy and vertical diffusion terms. The next terms on the RHS represent dissipation.

The turbulent exchange coefficient for momentum is expressed in terms of TKE and energy-dissipation using the Kolmogorov equation

$$K_m = \alpha_{e\varepsilon}\ E^2/\varepsilon, \quad (4)$$

where $\alpha_{e\varepsilon} = \alpha_2 = 0.046$ is a universal coefficient. In ocean and atmosphere modeling practices, $\alpha_{e\varepsilon}$ and α_2 may be varied to provide a realistic relationship between turbulent and thermo-dynamical structures. The set of constants α and β link the exchange coefficients for buoyancy and transport with K_m as follows

$$K_h = \alpha_3\ K_m\ ;\ K_{\varepsilon h} = \beta_3\ K_m\ ,\ K_e = \alpha_4\ K_m\ ;\ K_\varepsilon = \beta_4\ K_m \quad (5)$$

The constants α and β have the following values (Ly, 1991): $\alpha_1 = 1.0$; $\alpha_2 = 0.046$; $\alpha_3 = 1.0$; $\alpha_4 = 0.73$ and $\beta_1 = 1.43$; $\beta_2 = 1.97$; $\beta_3 = 1.45$; $\beta_4 = 0.73$

b. Wind-Wave-Turbulence-Current Relations

In the ocean mixed layer, surface wave breaking is an important source of turbulent energy, supplementing shear production. Wave breaking plays an important role in enhancing TKE and ε in the upper ocean layer. This version of the wave parameterization is based on results of both experimental and numerical studies, which show that breaking waves strongly enhance TKE and ε. This wave parameterization also incorporates a boundary condition for velocity across the interface.

Based on conservation of energy and similarity theory (Ly, 1986), breaking wave effects can be incorporated in equation for the TKE flux. Using a wave breaking condition model (Longuet-Higgins, 1969; Komen el al., 1994), the oceanic TKE at the interface can be written in terms of momentum flux and wave parameters. A similar equation can be written for ε. The current-wave relationship can be obtained from the equation for the energy fluxes (Ly, 1986). In these equations, if h = 0 (no waves), we have traditional conditions for TKE, ε, and velocity at the interface (the wave layer becomes an interface surface in this case). The wave-dependent roughness length (1) is used in the model.

The surface boundary conditions of the NAM ocean model include wind stress, heat and salinity fluxes. The bottom boundary conditions for TKE and ε, heat and salinity fluxes all approach zero. There are also conditions for bottom stress, which is determined by matching velocities with the log law of the wall (Blumberg and Mellor, 1987).

c. Ocean Circulation-Wave Coupling

The NAM model for the FWC region is used in a circulation-wave coupling study with idealized wave height and wave age fields. The study is focused on the sensitivity of the current field to the surface waves and on demonstration the capability of the NAM model to reproduce an observed upwelling feature for the FWC region. The model has 91 by 61 by 50 grid points to cover a domain from 86.5W-81.5W and 26.0N-28.0N. The model has realistic topography. The September temperature and salinity climatology is used to initialize the model. A horizontally homogeneous upwelling-favorable (northerly) wind stress of 2-dyne cm-2 is given. No wind stress curl and no surface heat flux are imposed. The temperature field simulation shows evidence of coastal upwelling along the shore, which is typical for the FWC region in September. Coastal upwelling is an observed and important physical phenomenon, which the numerical model can reproduce.

4. SUMMARY

A turbulence closure with the new wave parameterization and wave-dependent roughness length is used for a coupled model and is tested against available data. The wave parameterization in the model is able to relate model parameters to wave parameters, which are standard outputs of wave prediction models. The NAM includes the turbulence closure with the wave parameterization and wave-dependent roughness length. The NAM model for the realistic FWC region is used in a circulation-wave coupling study with idealized wave height and wave age fields.

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